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X-ray Optics for Science and Technology

Final Technical Report
for the period
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Prepared for the

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Washington, D.C. 20332-6448

Funded by an AFOSR Center of Excellence grant, the University of California has conducted research on soft x-ray physics, optics and applications thereof to the physical and life sciences. The work was led by faculty with joint appointments at the University of California at Berkeley (UCB) and the Lawrence Berkeley Laboratory (LBL). The program involved seven Ph.D. students and 45 undergraduate students from several UCB departments (Physics, Electrical Engineering, Materials Science, Nuclear Engineering, Biophysics) as well as the new Ph.D. program in Applied Science and Technology. With support from the Air Force Office of Scientific Research, over a six-year period, the University was able to develop a student research and training program second to none. The University supported this effort with several new courses, extensive class notes in publication form, and initiation of a new Ph.D. program in Applied Science and Technology (AS&T), which has recently been approved after a (parallel) five-year development program. In combination with support from the Department of Energy (DOE), and, more recently, DOD's Advanced Research Projects Agency (ARPA), a world leadership research group has been established, the Center for X-ray Optics (CXRO), which holds the world's record for highest resolution soft x-ray microscopy (300 Å); maintains leadership in biomicroscopy and spatially resolved materials studies; produces reflective optics in the soft x-ray and extreme ultraviolet (EUV), which are among the best in the world; participates in an EUV lithography program which will permit the future industrial evolution from visible and ultraviolet microchip patterning to EUV nanochip production; and offers one of the nation's strongest programs for student training in the emerging fields of nanostructure fabrication for materials science, quantum electronics and biomicroscopy. A recent review article from *Physics Today* (August 1992), which highlights some of these activities, is attached, along with the most recent (titled "1992", but document date is August 1993) annual report submitted to AFOSR, as well as other materials relevant to the AFOSR program.

As part of the training program to bring students into this new research area, several new courses have been initiated on the UCB campus: 1) Introduction to X-ray Physics and Technology (3 units); 2) Soft X-rays, Nanostructures and Applications (1 unit); X-ray Microscopy and EUV Lithography (1 unit); and 4) Applied Science and Technology Seminar (1 unit). Class notes for (1) above have been prepared and are still evolving. These now include seventeen chapters totaling more than 300 typed pages, with text, equations, diagrams, illustrations and appendices on subjects extending from refractive index and scattering at x-ray wavelengths, to sources, optics and other modern techniques, to applications in the physical and life sciences.

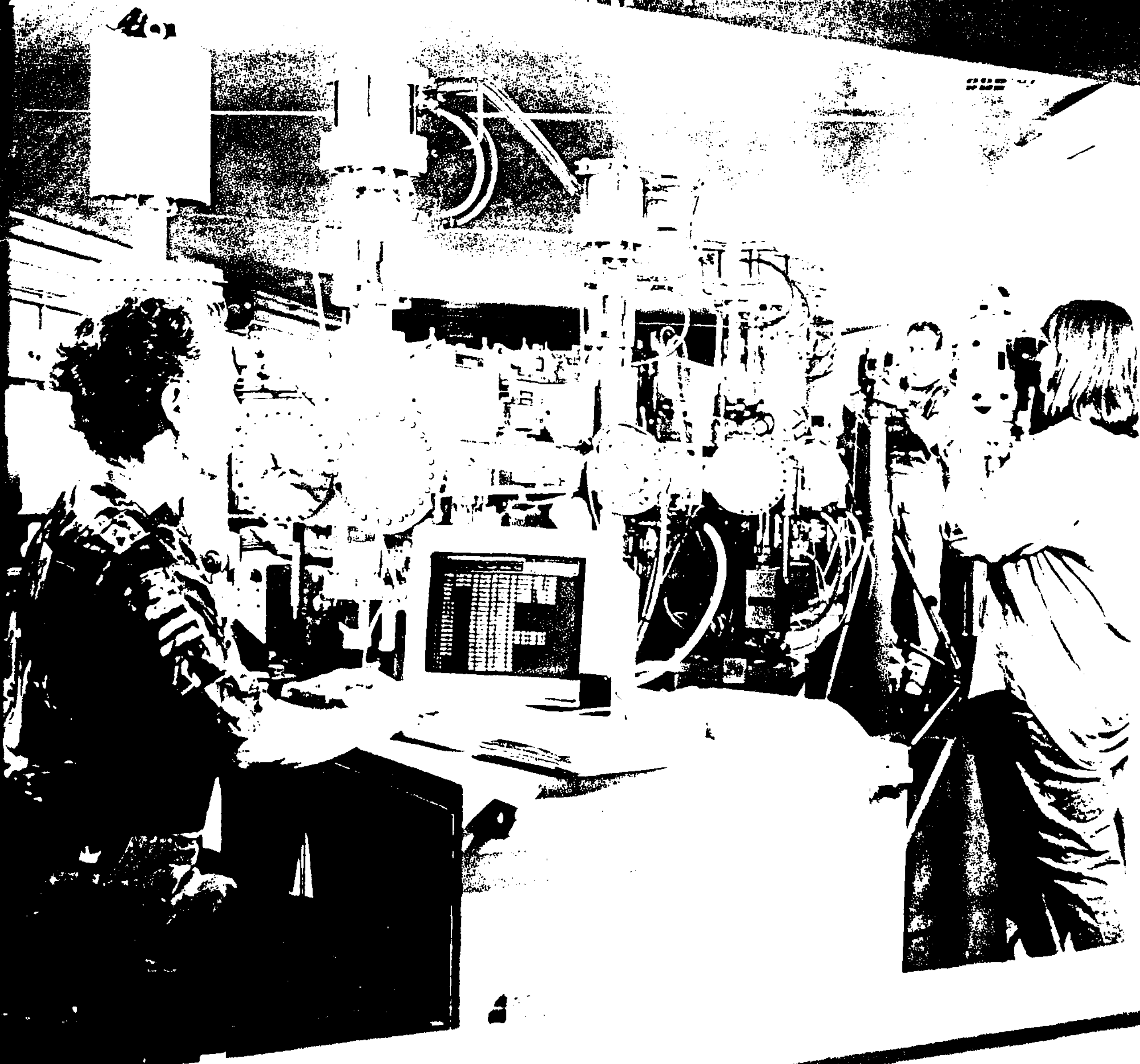
The University of California at Berkeley has clearly made a major commitment to this new area. A new Ph.D. program in Applied Science and Technology (AS&T) has been instituted at UCB, largely paralleling the AFOSR student training program. Announcements of the new program are attached. AS&T is interdisciplinary in nature. It closely reflects the broad goals of meeting future US needs for skilled scientists and engineers, while specifically encouraging research in areas of short-wavelength radiation and nanostructure fabrication, which are clearly on the forefront of societal and industrial needs, but which (until now) did not have a specific home base, which is requisite for success on a university campus.

Ph.D. students have been engaged in the AFOSR grant from its beginning. Yan Wu, a recent Ph.D. in Physics, studied phase transitions of materials under high pressure by focusing x-rays into the confines of a diamond anvil cell and observing the resultant diffraction. He now works at IBM Almaden. Tai Nguyen just completed a Ph.D. in Materials Science, studying the interface definition and stability in nanometer-period multilayer mirrors. He is currently engaged in post-doctoral research and teaching on the campus. Khanh Nguyen will soon complete a Ph.D. in Electrical Engineering and Computer Science (June 1994), studying defect printability as might occur in reflective masks for EUV lithography of 0.1 micron nanochip patterns. Khanh has just accepted a position at Intel. Kaarin Goncz just completed a Ph.D. in Biophysics, based on her research in the applications of x-ray microscopy to a biological study of secretion granules. Raul Beguiristain is about one year from completing a Ph.D. in Nuclear Engineering centered on high x-ray flux thermal loading as encountered with undulator radiation from high brightness synchrotron radiation sources. Max Wei is also about one year from completing a Ph.D. in Electrical Engineering and Computer Science. He has been using coherent undulator radiation at soft x-ray wavelengths (20 Å) to write fine periodic patterns for the study of quantum confined electron transport in future FET's. The program has also trained 45 undergraduate students by including them as research assistants in the various programs. Most have been authors on scientific papers and have gone on to graduate study or work in industry.

In summary, the AFOSR program has provided very valuable support for research and training in x-ray microscopy, EUV lithography and other related activities which we believe build a strong support base for future US. industrial activities, while providing a world class research capability for the US. in areas of short wavelength and nanoscopic structures which become more important each year.

PHYSICS TODAY

PART 1



PART

COVER: Portions of the electron storage ring and several photon-beam ports of the Advanced Light Source at Lawrence Berkeley Laboratory, as seen through its radiation shield wall. The ALS is one of several third-generation synchrotron facilities under construction worldwide. David Attwood's article on page 24 summarizes new research opportunities in the life and physical sciences based on recent developments in x-ray optics, x-ray lasers and synchrotron radiation.

NEW OPPORTUNITIES AT SOFT-X-RAY WAVELENGTHS

Advances in synchrotron radiation, x-ray lasers and x-ray optics permit new studies in the life and physical sciences at spatial resolutions of hundreds of angstroms.

David Attwood

A once dark region of the electromagnetic spectrum is now becoming very bright. The soft-x-ray spectral region, nominally extending from wavelengths of several angstroms to several hundred angstroms and including photon energies from tens of electron volts to several thousand electron volts, is providing many new research and development opportunities in the physical and life sciences and in industry. The move toward shorter wavelengths is driven in part by the desire to see and write smaller features. But the numerous and distinct atomic resonances in this region of the spectrum also provide for elemental identification and, in some cases, chemical sensitivity. (See the article by Bernd Crasemann and François Wuilleumier in PHYSICS TODAY, June 1984, page 34.) Developments in x-ray optics and new sources of high-brightness, partially coherent radiation make it possible to study materials and biological samples with feature sizes of several hundred angstroms.

With soft-x-ray microscopes, biologists can hope to see, in a near-native aqueous environment, structural features far beyond the resolving power of the visible-light microscope, and perhaps even motion. With recent soft-x-ray images discerning features as small as 300 Å in gold test patterns, we can envision the day when we gain new insights into the expression of genetic information encoded in DNA through observations of the higher-order packing and dynamics of chromatin in a near-native environment.[1] Figure 1a shows a chromosome image with 600-Å resolution, obtained at a wavelength of 24 Å.

In the physical sciences, new opportunities are arising in areas such as materials science, solid-state physics, electronic device physics and the industrial pursuit of nanoelectronic integrated circuits. X-ray photoemission microscopes are just becoming available to study elemental distributions and chemical states at material interfaces.[2] The possibility of studying quantum-confined transport in atomically defined channels with focused, spatially resonant excitation is just over the horizon. As the microelectronics industry moves toward faster, more compact electronic structures with feature sizes below 2000 Å, the need for shorter wavelengths is obvious. Nanoelectronic devices that have gate regions on the order of 1000 Å wide and 50 Å deep and whose charge transport depends on small quantities of both dopants and impurities will surely require new analytic tools combining spatial resolutions of several hundred angstroms and high chemical sensitivity. (See the article by Henry I. Smith and Harold G. Craighead in PHYSICS TODAY, February 1990, page 24.)

Optics and undulators

How has the soft-x-ray spectral region become so fertile for scientific and technological endeavors? The answer is that the requisite tools—thin windows, high-resolution lenses, optical coatings, lasers and undulators that generate x rays of high brightness and interesting coherence properties—are now becoming available.[3]

Advances in fabrication technology now make it possible to build the soft-x-ray equivalent of an early visible-light microscope. Materials scientists have contributed an ever improving capability to produce optical coatings comprising alternating layers of materials with

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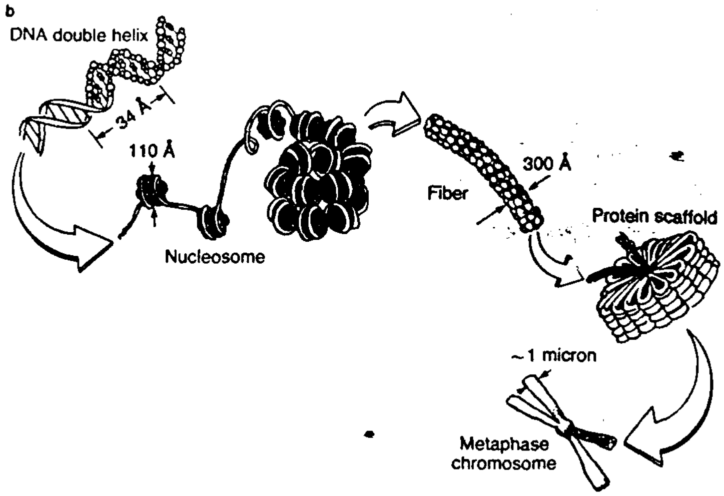


Chromosome and its structure. **a:** Image of a polytene chromosome from a larva of *Chironomus thummi* obtained at 24 Å exhibits the large-scale band structure familiar from visible-light microscopy—but also shows 600-Å fibers for the first time in an aqueous environment. The column is about 5 microns in diameter. (Courtesy of Günter Schmahl, University of Göttingen.) **b:** The packing and dynamics of chromatin—DNA and its associated proteins—are believed to play a strong role in genetic expression. The ever improving spatial resolution of soft-x-ray microscopy will allow the imaging of many critical features not yet seen in an aqueous environment. **Figure 1**

thicknesses measured in atomic dimensions. (Reflection at normal incidence requires single-layer thicknesses of approximately $\lambda/4$, where λ is the wavelength in vacuum.) Mirrors of alternating layers of molybdenum and silicon have exhibited 60% reflectivity in several laboratories.[4]

The microelectronics industry has contributed the capability to manufacture complex two-dimensional structures of gold and other materials with feature sizes approaching 100 Å. One can use such structures to make diffractive Fresnel zone-plate lenses with spatial resolutions limited primarily by the outer-zone width Δr, so that focusing and image formation are now possible to very high resolution at soft-x-ray wavelengths. Figure 2a shows a recent contribution to state-of-the-art x-ray optics: a zone-plate lens used to observe 300-Å features.[5]

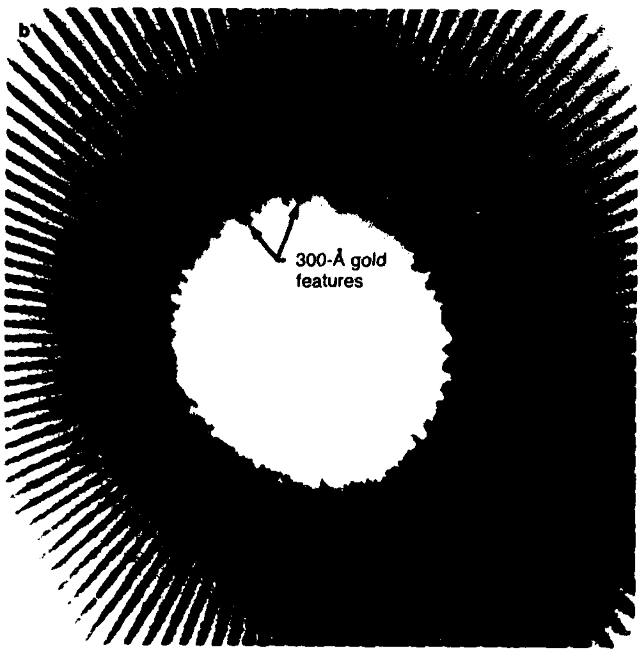
To exploit the emerging optics, one needs bright sources of soft x rays. The high-energy-physics community, through its pursuit of particle accelerators and storage rings, has made a major contribution with the development of undulator radiation.[6] As figure 3 indicates, when highly relativistic electrons of energy $E = \gamma m_0 c^2$ traverse a periodic magnet structure—an "undulator"—of period λ_u, they generate x rays in a very narrow central radiation cone. Here γ is the familiar $1/\sqrt{1-\beta^2}$, where $\beta = v/c$, v being the electron velocity and c the velocity of light in vacuum. The on-axis wavelength of the x rays is shorter than the magnet period λ_u by a factor $2\gamma^2$.

One can understand this very large wavelength reduction factor in relatively simple terms by first considering the radiation process in the frame of reference moving with the average velocity of the electrons and then considering the forward Doppler shift in the laboratory frame of reference. As the electrons traverse the periodic magnet structure, they execute a near-sinusoidal motion of period λ_u. As seen in the frame of reference moving with the electrons, the period is Lorentz-contracted to a value $\lambda' = \lambda_u/\gamma$ (just like the well-known meter stick). In this moving reference frame, the oscillating electrons emit a classical dipole radiation pattern of frequency $f' = c/\lambda'$, with a relative bandwidth $\lambda'/\Delta\lambda'$ equal to the number of periods N. Observed in the laboratory frame of reference, this dipole radiation undergoes a very strong Doppler shift due to the highly relativistic motion of the electrons toward the observer. This has two important effects: The usually broad angular radiation pattern observed in the electron frame of reference is folded into a very narrow radiation cone in the laboratory frame, and the observed wavelength is relativistically Doppler-shortened to a value of $\lambda = \lambda'\gamma(1-\beta\cos\theta)$, where θ is measured from the axial direction of motion. In the highly relativistic limit, with $1-\beta$ approaching $1/2\gamma^2$, one obtains the on-axis wavelength $\lambda = \lambda_u/2\gamma^2$.

For the Advanced Light Source under construction at Lawrence Berkeley Laboratory, which will have a nominal electron-beam energy of 1.5 GeV, γ is approximately 3000, providing a wavelength contraction factor $2\gamma^2$ of about 2×10^7! For an undulator with a 3.9-cm period at the ALS, one expects to generate soft x rays in the 20–50-Å wavelength region. Accounting for off-axis motion in the periodic magnetic field leads to a reduced average axial velocity, which affects both the Lorentz contraction and Doppler shift and thus leads to somewhat longer wavelengths. After one makes these corrections, the observed wavelength as a function of angle is

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right) \qquad (1)$$

where $K = eB_0\lambda_u/2\pi m_0 c$ is a nondimensional measure of



X-ray lens and image. a: Fresnel zone-plate lens with a 300-Å outer-zone width. (Courtesy of Erik Anderson, Lawrence Berkeley Laboratory.) **b:** Soft-x-ray (24 Å) image of a radial test pattern showing 300-Å gold features. (Courtesy of Werner Meyer-Ilse, Lawrence Berkeley Laboratory.) **Figure 2**

the magnetic field strength B_0 in a periodic magnet structure.[7] This formula illustrates the substantial $2\gamma^2$ relativistic shortening of both the observed wavelength and the longer off-axis ($\theta \neq 0$) wavelengths within the narrow radiation cone. The magnetic field strength term $K^2/2$ in equation 1 is important in that it provides a mechanism for tuning the wavelength of the undulator radiation.

With the ALS operating at its design conditions, the 3.9-cm-period undulator is expected to generate an average power of approximately 1 watt in a 1% relative bandwidth and within a nominal central radiation cone of angle $1/\gamma\sqrt{N} = 40$ microradians. The cross section of the beam is expected to be elliptical, with nominal 60- and 300-micron rms minor and major radii. With 35-picosecond pulses (full width at half maximum) every 2 nanoseconds, the ratio of peak power to average power will be about 50. A sister facility under construction at Argonne National Laboratory, the Advanced Photon Source, will operate with a beam energy of 7 GeV and produce undulator radiation at concomitantly shorter wavelengths in the hard-x-ray region of the spectrum. Undulator radiation at the APS will extend high-brightness x rays to wavelengths shorter than 1 Å, providing unique opportunities in protein crystallography, materials microprobes and other applications of hard x rays.[8]

Soft-x-ray lasers

The development of soft-x-ray lasers has been very exciting. Shorter-wavelength lasing has been pursued ever since the demonstration in 1960 of the first ruby laser at 6943 Å. In the following 20 years, achieved wavelengths progressed toward 1000 Å, a reduction of only about a factor of 7. Then in 1984, following early research in England and the USSR, two groups from the plasma physics community, working with laser-produced plasmas more familiar to the inertial fusion community, observed lasing at 182 Å and 206 Å, respectively, a step of an additional factor of 5 toward shorter wavelengths.[9,10] Both teams observed high-gain, single-pass lasing without the use of mirrors or mode-controlling optics. In each case the lasing medium was a hot, dense plasma created by a short-duration, high-power laser pulse.

In one of the experiments, done at Princeton University, recombination lasing at 182 Å was observed in a plasma formed by focusing a 300-joule, 50-nsec CO_2 laser pulse onto a solid carbon target.[9] As the fully stripped carbon atoms recombined with electrons in the cooling, magnetically confined plasma, population inversion occurred between the principal quantum number $n = 3$ and $n = 2$ states of single-electron carbon. Lasing at 182 Å was observed in the axial direction in a 10–30-nsec pulse of 5-milliradian divergence, with a peak power of 100 kW.

At the same time, researchers at Lawrence Livermore National Laboratory were experimenting with collisionally excited, highly stripped selenium atoms in a laser-produced hot, dense plasma.[10] (See figure 4.) In this case, half-nanosecond pulses of 5320-Å visible light from a frequency-doubled, high-power neodymium-doped-glass laser illuminated a thin selenium film in an elongated-line focus, typically 200 microns wide by 1 cm long. At optimal irradiation intensity, the group was able to produce favorable plasma conditions for x-ray lasing. These included an electron temperature in the 600–1000-eV range, electron densities of several times 10^{20} electrons/cm^3 and transverse gradient lengths on the order of 100 microns. Having a high electron temperature assures not only that appropriate atomic transitions are excited but also that the lasing medium is a fully ionized plasma. The high electron density results from a balance between the requisite collisional excitation and gain on the one hand and collisional depopulation of long-lived excited states on the other. A single charge state prevails in the partially stripped selenium atoms, because while the loosely bound outer electrons are easily removed in collisions, the more tightly bound closed-shell electrons are not. The ionization bottleneck occurs as the electron removal process brings the ion close to the closed-shell "neon-like" ten-electron configuration. For selenium, which has atomic number $Z = 34$, this corresponds to a $+24$ charge state.

Collision and recombination rates in these high-density plasmas are sufficient to raise many of the neon-like atoms from their $1s^2 2s^2 2p^6$ ground state to various $n = 3$ excited states—for example, to $1s^2 2s^2 2p^5 3p$. Population inversion occurs among the excited states primarily because of substantial differences in radiative decay rates. While $3s \rightarrow 2p$ transitions are allowed and thus occur quickly, in less than 1 picosecond, $3p \rightarrow 2p$ transitions are forbidden and thus have lifetimes on the order of 100 picoseconds. Hence a population inversion is established between the 3p and 3s states. Although spontaneous emission occurs in all directions from these long-lived excited atoms, high-gain amplification occurs only in the elongated plasma direction, as figure 4a indicates. Among the strongest lines observed in the early experiments were those at 206 Å and 209 Å. In later experiments at these wavelengths, lasing has approached saturation at output levels of about 10 megawatts in single, subnanosecond pulses.

In further experiments involving collisional excitation, the Livermore researchers have demonstrated lasing in a variety of atoms ionized to a nickel-like 28-electron configuration.[11] Figure 4b shows a lasing line observed at 44.83 Å, corresponding to a $4d \rightarrow 4p$ transition in nickel-like tantalum ($Z = 73$, 28 electrons, $+45$ charge state). This transition lies on the nonabsorbing side of the carbon K edge, where absorption and thus radiation damage are minimized. It therefore is of interest for holographic experiments in the imaging of biological specimens.[12] In the experiments to date at a wavelength of 44.83 Å, power in excess of 100 kilowatts has been obtained in single subnanosecond pulses with a very narrow relative bandwidth—on the order of 10^{-4}—but with a very high spatial mode structure. In future experiments, various groups around the world plan to explore the use of cavity mirrors[3] and various mode-selecting techniques to improve the coherence properties of these lasers, enhance output at shorter wavelengths and provide higher repetition rates. With these improvements, researchers hope to pursue high-resolution, subnanosecond imaging of biological objects using multiview two-dimensional microscopy as well as holographic techniques. Preliminary two-dimensional subnanosecond images of sperm cells have already been obtained.[13]

Brightness and coherence

Brightness and coherence specifications are critical to the sophisticated exploitation of opportunities in any region of the electromagnetic spectrum. If we define "brightness" as the radiated photon flux (or power) per unit area per unit solid angle, then in a perfect optical system brightness is a conserved quantity. While x-ray optical systems are lossy and approach unaberrated performance in only the best of circumstances, brightness is still a powerful concept for characterizing sources and their utility in various imaging and probing experiments.

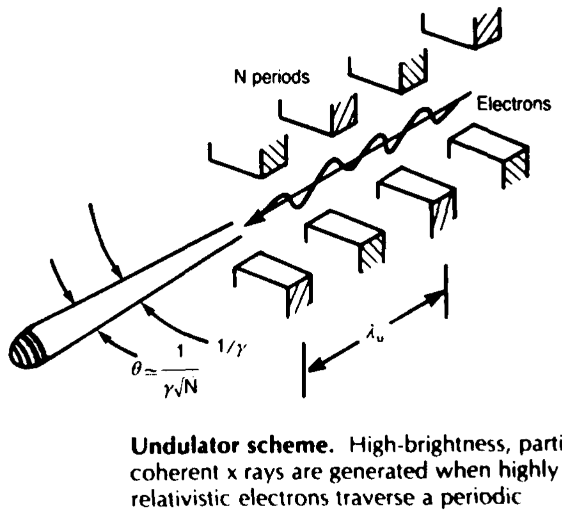
In an imaging system the product of size d and half-angle θ is conserved between conjugate planes, for instance between the object or source plane and the image plane. From this it follows that the product of the area of the item being imaged and the associated solid angle, $\Delta A \Delta\Omega$, is the same in conjugate planes. Further, if the system is nonabsorbing, then the brightnesses are equal in the two planes. For experiments in which spectral bandwidth is also important, as when one is exploiting or investigating atomic structure, we extend our definition of brightness to spectral brightness $B_{\Delta\omega/\omega}$:

$$B_{\Delta\omega/\omega} = \frac{F}{\Delta A \, \Delta\Omega \, \mathrm{BW}} \tag{2}$$

This expression gives the photon flux F per unit area ΔA per unit solid angle $\Delta\Omega$ per unit of relative spectral bandwidth BW. The photon flux is measured in units of photons per second or power, and the relative bandwidth $\Delta\lambda/\lambda$ is often expressed as a percentage.

For experiments involving high-resolution microscopy, in which the available photon flux must be transferred to a given plane—such as a biological sample—within limited spatial and angular constraints, source brightness is a critical quantity. For microprobe focusing experiments, in which the spot size d is to be minimized and the beam's angular extent θ is constrained by the numerical aperture of the lens, it is important to have a source of sufficiently small "phase space" product $d \cdot \theta$. In a scanning microscope, for example, we require that d be minimized for best spatial resolution, and thus we ask ourselves what the minimum achievable phase-space product is. This brings us to questions involving diffraction and spatial coherence, whose answers in turn lead us to understand that the minimum phase space achievable is limited by the nonzero wavelength employed.

The ability to focus radiation or to form interference patterns is dependent on phase and amplitude variations

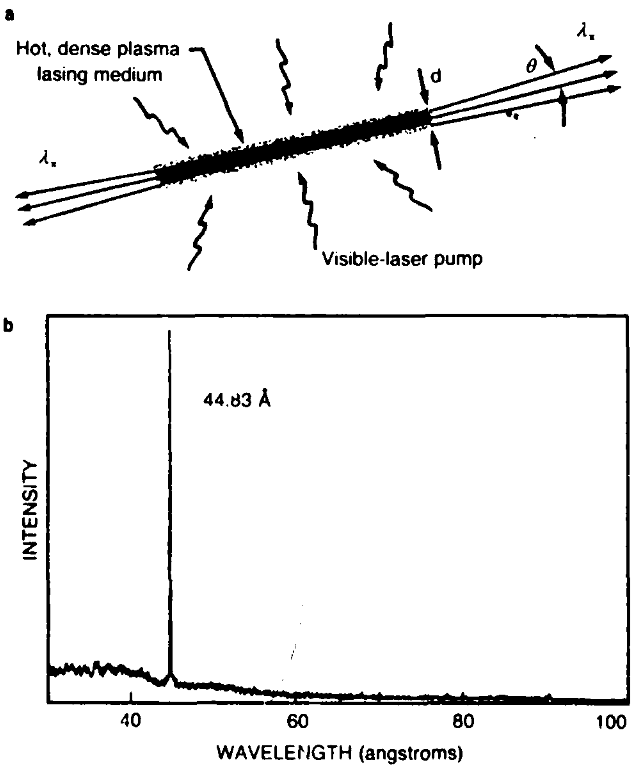


Undulator scheme. High-brightness, partially coherent x rays are generated when highly relativistic electrons traverse a periodic magnet structure. **Figure 3**

throughout the radiation field. In general, simple phase distributions approaching those of plane or spherical waves are of greatest interest in these applications. Real laboratory sources, however, have radiation fields with more complex phase relationships that are well defined over only limited spatial and temporal scales. Such fields are referred to as "partially coherent."[14]

In the theoretical limit of a point source oscillating at a single frequency for all time, the radiated field quantities would be perfectly correlated everywhere. That is, if one knew the field amplitude and phase at a given point and time, then one would know these quantities at all points and for all time. In this limiting case the radiation field is said to be "coherent." Real physical sources, however, are spatially distributed and radiate with a finite spectral bandwidth. Consequently, strong phase correlations between field amplitudes are in practice restricted to a "region of coherence."

Marching soldiers provide a convenient analog to these concepts. The coherent limit corresponds to all soldiers marching in perfect step. In the presence of a strong wind, however, some soldiers might not hear the leader calling the cadence. In that case those soldiers close enough to hear would remain in step, while those farther away would become out of step—creating a region of coherence near the leader. Clearly the complete absence of cadence would result in incoherence: zero correlation among the steps of any soldiers.



X-ray lasing technique and result. **a:** Hot, dense plasma is created by a subnanosecond visible-light heating pulse. **b:** Lasing at 44.83 Å, based on collisional excitation of nickel-like tantalum ions in a hot, dense plasma, as observed at Lawrence Livermore National Laboratory. (Courtesy of Brian MacGowan.) **Figure 4**

Coherence length

In cases where there is a relatively well-defined direction of propagation, it is convenient to decompose the region of coherence into orthogonal components, one in the direction of propagation and one transverse to it. In the direction of propagation it is common to describe a longitudinal, or "temporal," coherence length l_{coh} over which given phase relationships are maintained. For a source of spectral bandwidth $\Delta\lambda$, one can define a coherence length

$$l_{coh} = \lambda^2/2\Delta\lambda \qquad (3)$$

where the numerical factor of $\frac{1}{2}$ results from both the spectral shape and the definition of $\Delta\lambda$. In the formation of interference patterns by amplitude dissection and recombination, as in holography and interferometry, it is important that differences in propagation lengths be less than the coherence length; otherwise one will not obtain high-contrast fringe patterns.

Transverse, or "spatial," coherence properties, however, are related to the finite size of the source and the characteristic emission angle. Here we are interested in phase correlation in planes orthogonal to the direction of propagation. It is instructive to consider the relationship of spatial coherence to spherical waves in the limit of phase being perfectly correlated everywhere. Clearly this limit corresponds to concentric spherical waves with constant phase across every spherical surface and with phase maxima separated by a wavelength in the outwardly propagating direction. Although somewhat restrictive, we consider the spherical case because it is common to our experience and yields a clear physical insight. With some appropriate bandwidth, and thus finite coherence length, such a spherical wave could provide a reference wave for encoding complex wavefronts, as in holography. Near-spherical waves can be focused to a spot size approaching finite wavelength limits, as in a scanning microscope, or collimated to travel with minimal divergence for use in precision diffraction experiments.

Full spatial coherence can be achieved with a spherical wavefront, which we can associate with a point source. We might then ask, How small is a point source? How small must our undulator electron beam or x-ray laser aperture be to provide spatially coherent radiation? We can obtain a simple estimate based on Heisenberg's uncertainty principle:

$$\Delta\mathbf{x}\cdot\Delta\mathbf{p} > \hbar/2 \qquad (4)$$

Here $\Delta\mathbf{x}$ is the uncertainty in position and $\Delta\mathbf{p}$ the uncertainty in momentum. Using equation 4 we can determine the smallest source size d resolvable with finite wavelength λ and observation half-angle θ. For photons the momentum is $\hbar\mathbf{k}$, where the scalar wavenumber $|\mathbf{k}|$ is $2\pi/\lambda$. If the relative spectral bandwidth $\Delta\lambda/\lambda$, which is equal to $\Delta k/k$, is small, then the uncertainty in momentum $\Delta\mathbf{p} = \hbar\Delta\mathbf{k}$ is due largely to the uncertainty in direction θ, so that for small angles $|\Delta\mathbf{p}| = \hbar k\theta$. Substituting into the uncertainty relation and identifying a source "diameter" $d = 2\Delta x$, we obtain the relationship

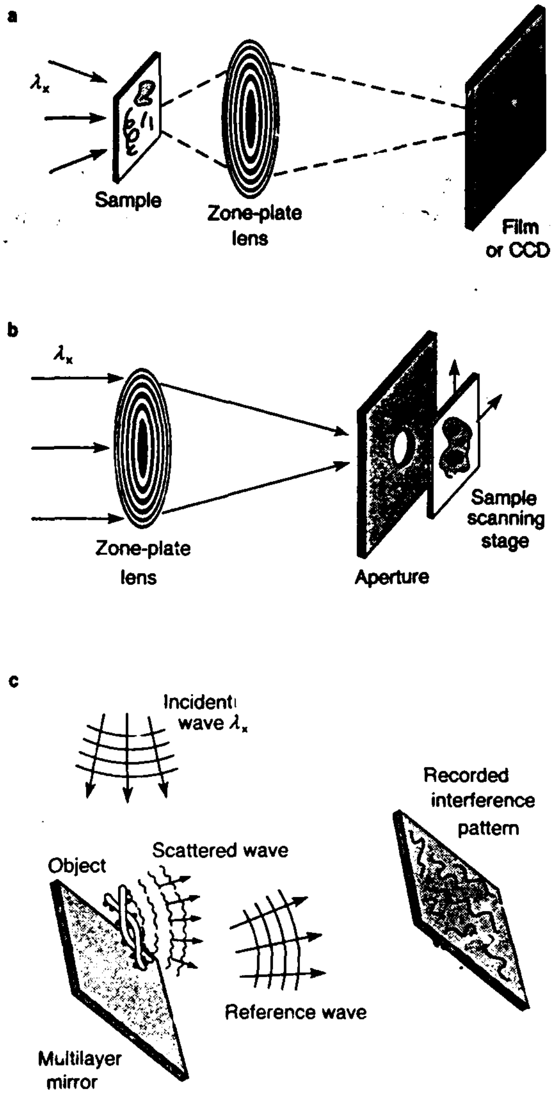
$$d \cdot \theta > \lambda / 2\pi \qquad (5)$$

which determines the smallest source size we can discern; that is, within the constraints of physical law we would not be able to tell if our "point" source were any smaller. Radiation satisfying the equality of equation 5 is said to be "diffraction limited"—that is, limited by the finite wavelength. To generate a spatially coherent spherical wave we must develop a source—at x-ray wavelengths—that approaches the limiting value of equation 5. For comparison, a laser radiating in a single transverse mode TEM_{00} satisfies this same condition when the waist diameter d and far-field divergence half-angle θ are written in terms of rms quantities.

In equations 2, 3 and 5 we now have convenient measures with which to assess the brightness and coherence properties of x-ray sources for applications involving high-resolution microscopy, holography and coherent optics. For example, the 3.9-cm undulator to be used at the Advanced Light Source is expected to produce continuously tunable, linearly polarized radiation in the 20–50-Å wavelength range with a time-averaged spectral brightness ranging from 10^{18} to 10^{19} photons $sec^{-1}\,mm^{-2}\,mrad^{-2}$ within a 0.1% relative spectral bandwidth. Furthermore, at a wavelength of 25 Å the phase-space product $d \cdot \theta$ is expected to be about 5 times the diffraction limit in the vertical plane and about 50 times the diffraction limit in the horizontal plane. Differences in the two planes result from the elliptical cross section and angular divergence of the electron beam. Thus for experiments at the ALS that benefit from spatially coherent radiation,[15] such as holography and scanning microscopy, one must consider the use of a spatial filter (perhaps just a pinhole) that would pass only the lowest-order TEM_{00} mode, albeit with a reduced photon flux. With a total power in the central radiation cone of about 1 watt in a 1% relative spectral bandwidth, spatial filtering would yield an average coherent power of about 4 mW, or a single-pulse peak coherent power of about 200 mW. Note that with a 1% bandwidth at 25 Å, the longitudinal (temporal) coherence length is about 0.25 microns. This can be extended significantly through the use of a high-resolution monochromator (with $\lambda/\Delta\lambda > 10^4$), to tens of microns if needed, but with further reduction of photon flux due to reduced bandwidth and instrumental efficiency. Efforts to exploit the partially coherent nature of undulator radiation are now under way in experiments at the National Synchrotron Light Source at Brookhaven National Laboratory.[16]

The x-ray lasers discussed earlier are also characterized by very high spectral brightness and interesting coherence properties. Of particular interest are their single-pulse, subnanosecond nature and the relatively narrow spectral width ($\Delta\lambda/\lambda \simeq 10^{-4}$) of their emissions. For example, the nickel-like tantalum laser demonstrated at Livermore[11] produces about 20 microjoules of 44.83-Å radiation in a single 200-psec pulse, giving a peak power of about 100 kW. A similar laser line at 43.15 Å has been demonstrated in nickel-like tungsten. The availability of these two wavelengths, just bracketing the 44-Å carbon K edge, offers an opportunity to optimize the ratio of scattering to absorption processes and provides the potential for wavelength differential microprobing. In addition, the very short pulse reduces the likelihood of blurring due to motion.

With a measured angular divergence 2θ of about 10 mrad and an estimated source size d of about 100 microns, the tantalum laser has a single-pulse spectral brightness (defined in equation 2) of about 4×10^{21} photons $sec^{-1}\,mm^{-2}\,mrad^{-2}$ within a 0.01% relative spectral bandwidth and has a phase-space product $d \cdot \theta$ ideal for short-pulse x-ray microscopy.[13] The phase-space product in these experiments is about 700 times the diffraction limit of $\lambda/2\pi$ for this wavelength in both planes. The single-pulse coherent power is thus on the order of 200 mW.



Imaging schemes. **a:** A soft-x-ray microscope requires brightness but not coherence. **b:** A scanning microscope requires spatially coherent radiation to achieve the smallest possible spot size. Spectral bandwidth in both cases is determined by the number of zones in the lens. **c:** High-resolution holographic imaging requires large-angle scattering, spatially coherent radiation and a coherence length sufficient for the geometry employed. **Figure 5**

Physical and life sciences

A major advantage of bright radiation is that it can be delivered, within the limits of wavelength and numerical aperture, to small regions. Thus much attention is being given to developing soft-x-ray microscopy as an extension of visible-light techniques but with a resolution between those of visible-light and electron microscopy—the so-called mesoscopic region. Figure 5 illustrates some of the major techniques being developed for high-resolution soft-x-ray microimaging.

Figure 5a is a schematic diagram of an x-ray microscope based on the use of a Fresnel zone-plate lens. This microscope requires radiation of very high brightness to illuminate small samples optimally. It is an analog of the visible-light microscope of an earlier age. Spatial resolution is set primarily by the wavelength λ and the lens's outermost-zone width Δr. Diffraction from the outer region of the lens sets the numerical aperture at $\lambda/2\Delta r$. To avoid chromatic aberration the relative spectral bandwidth $\Delta\lambda/\lambda$ of the source must be matched to the number of radial periods of the lens. Thus the illuminating radiation must be spectrally bright both for proper use of the microscope and for spectral analysis of the sample. Lens efficiency, which is on the order of 5–20% for zone plates, affects all microscopes that use such lenses but particularly this configuration, as only a portion of the radiation passing through the sample contributes to image formation. The remainder is lost to undiffracted radiation and higher-order diffraction. This inefficiency becomes particularly important for radiation-sensitive materials.

A major advantage of this type of soft-x-ray microscope is its simplicity and its ability to produce high-resolution images. A group from the University of Göttingen obtained the gold spoke pattern in figure 2b, showing 300-Å features, with its x-ray microscope at the BESSY synchrotron facility in Berlin.[17] The x-ray microscope image in figure 1a is of a hydrated but fixed polytene chromosome isolated from a larva of the fly *Chironomus thummi*. It was obtained at a wavelength of 24 Å, where water is relatively transparent, and shows both the broad banding features familiar from visible-light microscopy and very fine chromatin fibers, some as small as 600 Å. With new zone-plate lenses of smaller outer-zone width and higher diffraction efficiency, it should be possible in the not-too-distant future to see 300-Å fibers in a near-native aqueous state. The ability to extend these studies will depend on the success of efforts to minimize and mitigate the effects of radiation damage, which increases rapidly with improved resolution, and to optically isolate specific regions within a thick specimen.

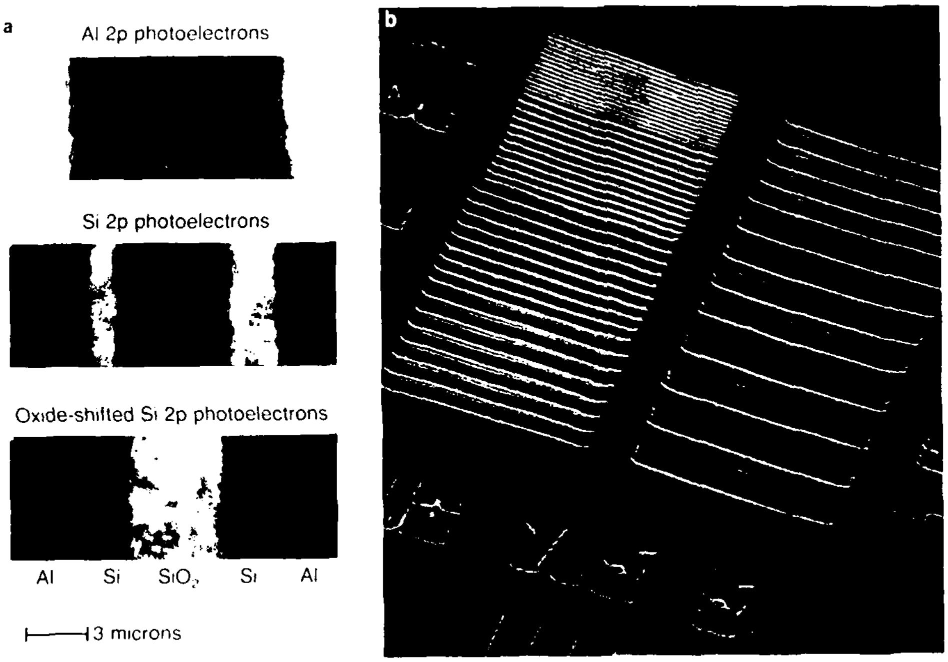
Scanning x-ray microscopes, illustrated schematically in figure 5b, are an important complement to the conventional microscope in that they minimize radiation damage, although at some cost in exposure time and in spatial resolution. Such microscopes achieve their spatial resolution by focusing radiation to the smallest possible spot size and then raster scanning the sample to obtain a two-dimensional image. The scanning technique lends itself conveniently to transmission, fluorescent and photoelectron microscopies.[18] An aperture that transmits to the sample only the focused radiation blocks undiffracted radiation and unwanted diffraction orders, thus minimizing radiation damage. But to achieve the smallest possible spot size in this microscope, the illuminating radiation must be spatially coherent, as described earlier. Thus current sources (and sources expected to be available soon) that generate radiation many times the diffraction limit use pinhole or far-field spatial filtering techniques, which significantly reduce the photon flux and further extend the exposure time. Lens numerical aperture, wavelength and aberrations affect the achievable resolution in the usual fashion in such microscopes.

In addition to extending classical optical microscopies to shorter wavelengths, there is the possibility of using holographic techniques, as figure 5c suggests. Several groups are already developing such techniques.[19] In principle these techniques provide the possibility of both three-dimensional imaging and higher resolution if scattering at sufficiently large angles is recorded and reconstructed. These pursuits involve many challenges, which include choosing the wavelength, preparing the sample to enhance scattering, and handling the increased radiation damage that follows when relatively weak scattering requires the use of a higher-intensity probe.

Figure 6 displays examples of microimaging. Figure 6a shows photoemission images of portions of a microelectronic device, obtained by tuning to 2p levels of aluminum and silicon. The images were produced in a materials science study using the Stony Brook–NSLS scanning photoemission zone-plate microscope at Brookhaven.[2] Other studies of the surface states of various materials are under way at the University of Wisconsin's Synchrotron Radiation Center, where multilayer coated reflective optics are used at somewhat longer wavelengths.[2]

Coated optics have emerged recently as a possible means of printing nanoelectronic circuit patterns using extreme ultraviolet light or soft x rays. (See PHYSICS TODAY, October 1991, page 17.) If successful, these xuv–soft-x-ray lithographic techniques would be used by the turn of the century for the manufacture of 1-gigabit memory chips with feature sizes as small as 0.1 micron. Progress toward this end is illustrated in figure 6b, which shows a 20:1-reduced pattern produced by projection lithography at 140 Å by an AT&T group working at the NSLS.[20] Substantial challenges lie ahead for the development of xuv optical systems that can maintain the required resolution over field sizes of several square centimeters. The development of high-repetition-rate, moderately high-power near-visible lasers would permit this work to be pursued with soft-x-ray emission from laser-produced plasmas.

Additional uses of coherent x-ray optical techniques have been proposed. One such technique combines soft-x-ray microfocusing with scanning tunneling microscopy. Together these provide the potential for mapping elemental surfaces with spatial resolution limited by the size of the tunneling tip.[21] Different elemental maps would be generated as the photon bath is tuned through the excitation energies of various atoms. Other opportunities, based on the use of "two color" pump–probe techniques involving picosecond soft-x-ray pulses and femtosecond visible-light pulses, include novel atomic probing and perhaps the development of subpicosecond switching techniques at x-ray wavelengths. At the ALS such studies would use single-pulse zone-plate-focused undulator radiation with power densities on the order of 10^9 W/cm^2 at a very high repetition rate. Additional possibilities include



Microimaging. a: Zone-plate photoemission is sensitive to elements and their chemical bonding in complex material structures. The structures shown here are similar to those incorporated in microelectronic devices. (Courtesy of Harald Ade, State University of New York, Stony Brook.) **b:** Nanoelectronic pattern transfer using 20:1 reduction optics at a wavelength of 140 Å has produced feature sizes down to 0.05 microns. (Courtesy of Richard Freeman, AT&T Bell Laboratories.) **Figure 6**

the spatially resonant excitation of quantum-confined structures and the development of generalized holographic projection techniques.

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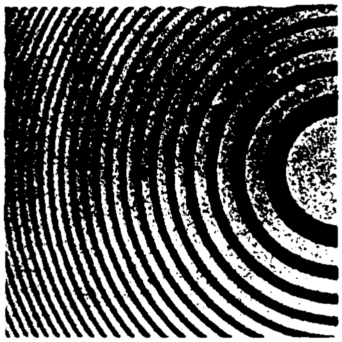

CENTER FOR X-RAY OPTICS

In 1992 the Center for X-Ray Optics (CXRO) continued its two complementary roles: demonstrating the capabilities and usefulness of the x-ray and ultraviolet regions of the spectrum and developing equipment and techniques to make those capabilities widely and readily available. Efforts continue to develop state of the art x-ray lenses and mirrors, monochromators optimized for high resolution and throughput, optical systems for the utilization of partially coherent radiation, and applications across the physical and life sciences.

High-resolution x-ray microscopy continues to be a prominent activity. Soft-x-ray microscopy based on Fresnel zone-plate lenses has provided images of features as small as 300 Å in experiments at the Berlin Electron Synchrotron (BESSY). Spatially resolved studies of materials have been conducted with colleagues at both Wisconsin and Brookhaven. Biomicroscopy studies have been explored with colleagues at Göttingen and Stony Brook. In the hard-x-ray regime, a microprobe, based on multilayer-coated reflective optics, has achieved 2-μm spatial resolution at the National Synchrotron Light Source (NSLS) and has been used in a large number of applications in the life and physical sciences. The microprobe is presently in use at ESRF in Grenoble, and will soon be used among the first experiments at LBL's newly commissioned Advanced Light Source (ALS).

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UNIVERSITY OF CALIFORNIA AT BERKELEY

Graduate Group in Applied Science and Technology

Programs of Study

Applied Science and Technology, a new program on the UC Berkeley campus, operates under the auspices of the College of Engineering's Interdisciplinary Studies Center.

The new program will have two major areas of emphasis, applied physics and mathematical sciences. Faculty members associated with the new program are drawn from several departments within the College of Engineering as well as from the Departments of Physics, Chemistry, and Mathematics. Topics of interest include the novel properties and applications of nanostructures, thin films and interface science, short wavelength coherent radiation, X-ray microimaging for the life and physical sciences, plasma physics and plasma-assisted materials processing, laser-induced chemical processes, laser probing of complex reacting systems, ultrafast phenomena, particle accelerators, nonlinear dynamics, chaotic systems, numerical methods, and topics in computational fluid mechanics and reacting flows. This program awards Ph.D. degrees.

Research Facilities

Graduate research in the AS&T Program will profit greatly from the multitude of state-of-the-art experimental facilities on the UC Berkeley campus and at the adjacent Lawrence Berkeley Laboratory. Among these facilities are the National Center for Electron Microscopy, with the world's highest resolution high-voltage microscope and a microfabrication lab for student work involving lithography, ion-implantation, and thin-film deposition; an integrated sensors laboratory; femtosecond laser laboratories; optical, electrical, and magnetic resonance spectroscopies; short wavelength laser and X-ray research laboratories; an unparalleled variety of material, chemical, and surface science analytic equipment; and a soon-to-be completed soft X-ray synchrotron dedicated to materials, chemical, and biological research based on high-brightness and partially coherent radiation. The interdisciplinary, collaborative nature of the AS&T Program provides ample opportunity to develop new research directions by making the best use possible of these facilities and of the other research instrumentation available to AS&T faculty members.

Financial Aid

Students are encouraged to apply for extramural (e.g., NSF) fellowships as well as for various others administered by the University. Research assistantships are available in projects supported by extramural grants or contracts. An effort is made to align the research assistant's interests with those of a faculty member working with extramural support.

Cost of Study

Fees, insurance, and tuition for 1993–94 total approximately $4370 for California residents and $12,070 for nonresidents.

Living and Housing Costs

Room and board in the San Francisco Bay area for the 1993–94 nine-month academic year average $4725–$6825. Books and supplies total about $400, and entertainment and miscellaneous expenses are about $1200. Costs are proportionately higher for the twelve-month academic year.

Student Group

Approximately 31,000 students, including close to 9,000 graduate students, are enrolled at Berkeley. The cosmopolitan student body includes about 1,900 international students from nearly ninety countries and about 3,500 students from states other than California.

Location

The University is located at the base of the Berkeley hills, looking across the San Francisco Bay to San Francisco. The San Francisco Bay Area has a tremendous variety of cultural and entertainment activities to suit all tastes and interests. Students have ready access to the Pacific Coast and beaches, and excellent skiing areas can be found 3½ hours east in the Sierra Nevada. The climate is cool in the summer, with no rainfall. Winters are mild, with intermittent rainfall and sunny days. It is an excellent working climate.

The University

The Berkeley campus of the University of California is the system's parent campus. It has an enrollment of 30,000, with 8,700 graduate students in 100 fields of study, and is noted for the academic distinction of its faculty, the high quality and wide scope of its research activities, and the variety and vitality of student activities. It is generally ranked by its academic peers as one of the best graduate institutions in the United States.

Applying

Complete applications, including transcripts, GRE scores, three letters of reference, and a statement of academic and professional goals, are due January 31 for the following fall. To obtain application forms, students should contact the address below.

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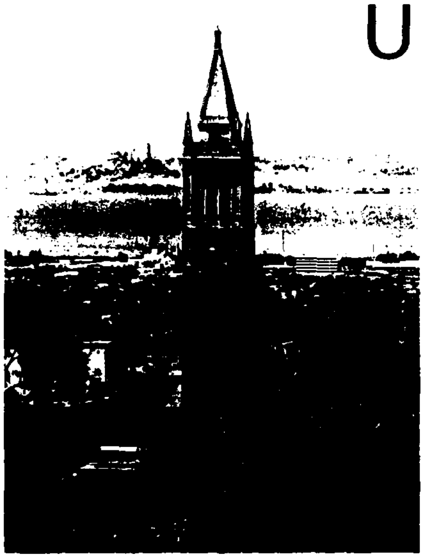
Eicke R. Weber, Department of Materials Sciences and Mineral Engineering (UCB), Materials Sciences Division (LBL). Defects in bulk and thin-film semiconductors, electronic and structural properties and their influence on device performance. (weber@garnet)

Alan Weinstein, Mathematics Department (UCB). Symplectic geometry, Hamiltonian structures, stability, connections between classical and quantum mechanics. (alanw@math.berkeley.edu)

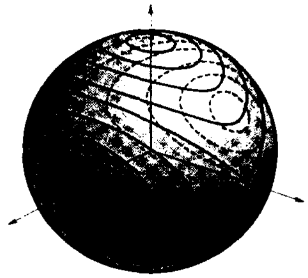
Richard M. White, Department of Electrical Engineering and Computer Science (UCB). Ultrasonics, micromachine sensing and actuation devices for physical, chemical, and biological applications.

UNIVERSITY OF CALIFORNIA AT BERKELEY

Graduate Group in Applied Science and Technology



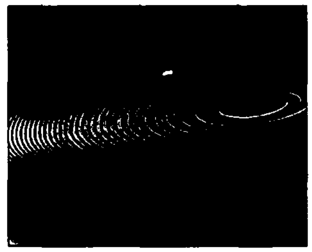
This new Ph.D. program on the Berkeley campus has two major areas of emphasis, applied physics and mathematical sciences. Faculty members associated with the new program are drawn from several departments within the College of Engineering as well as from the Departments of Physics, Chemistry, and Mathematics. Topics of interest include the novel properties and applications of nanostructures, thin films and interface science, short wavelength coherent radiation, microimaging for the life and physical sciences, plasma physics and plasma-assisted materials processing, laser-induced chemical processes, laser probing of complex reacting systems, ultrafast phenomena, particle accelerators, nonlinear dynamics, chaotic systems, numerical methods, and topics in computational fluid mechanics and reacting flows.



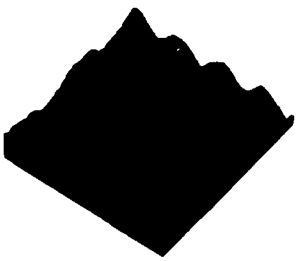
Dynamics of a rigid body

Micromechanical comb-drive

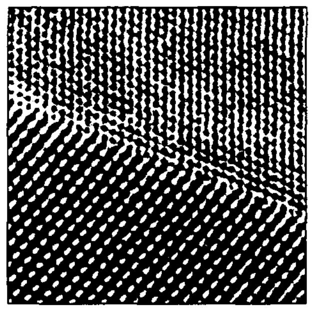
Graduate research in the AS&T Program will profit greatly from the multitude of state-of-the-art experimental facilities on the UC Berkeley campus and at the adjacent Lawrence Berkeley Laboratory. Among these facilities are the National Center for Electron Microscopy, with the world's highest resolution high-voltage microscope; a microfabrication lab for student work involving lithography, ion-implantation, and thin-film deposition; an integrated sensors laboratory; femtosecond laser laboratories; optical, electrical, and magnetic resonance spectroscopies; short wavelength laser and x-ray research laboratories; an unparalleled variety of material, chemical, and surface science analytic equipment; and a soft x-ray synchrotron facility dedicated to materials, chemical, and biological research based on high-brightness and partially coherent radiation. The interdisciplinary nature of the AS&T Program provides ample opportunity to develop new research directions by making the best possible use of these facilities and of the other research instrumentation available to AS&T faculty members.



Soft x-ray zone plate lens



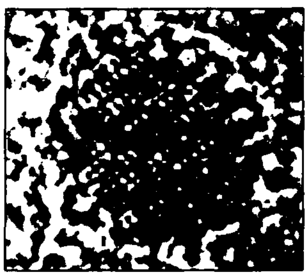
GaAs (110) surface



Aluminum-germanium interface

For general information and application materials, mail the attached postcard. For futher information, address e-mail to Marie Mayne (mayne@coe.berkeley.edu).

Please send completed applications, including transcripts, GRE scores, three letters of reference, and a statement of academic and professional goals, by January 31 for the following fall.



CdSe nanocrystal

Vortex dynamics

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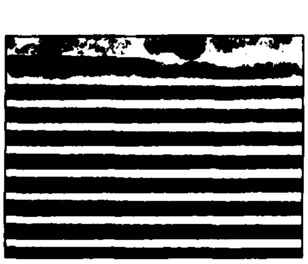
Undergraduate School Degree/Date of Conferral

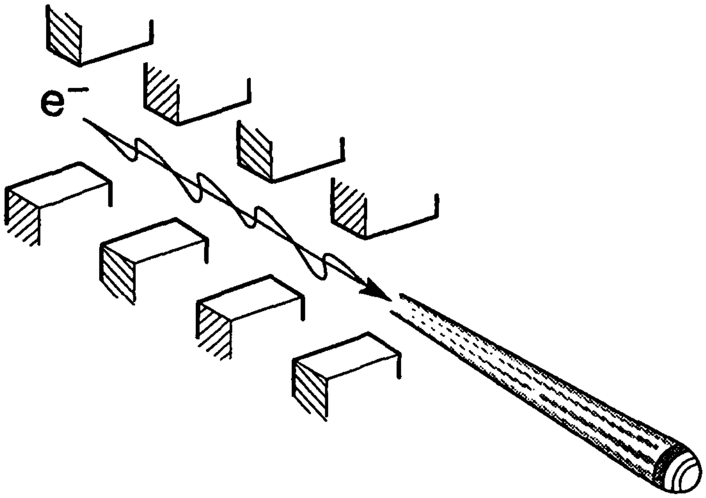


EUV lithography mirror

If all postcards are gone, write to:

Applied Science and Technology
230 Bechtel Engineering Center
University of California
Berkeley, California 94720

Introduction to X-Ray Physics and Technology



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David Attwood
E-210
College of Engineering
University of California
Berkeley, CA 94720

November 1991

Introduction

These class notes for X-Ray Physics and Technology have been evolving since the class was first offered in 1986. During the Spring 1990 class, students agreed to help bring the notes into a more readable form, and in some cases introduce new material. This document is a snapshot in time of the evolving class notes one year later.

The class itself, now offered as E-291 in UC Berkeley's College of Engineering, is a graduate level one semester course designed to introduce graduate students and advanced undergraduates to scientific and technological advances involving x-rays. Particular attention is paid to emerging opportunities with longer wavelength "soft x-rays," just beyond the ultraviolet region of the spectrum. The course might equally well be titled "Short Wavelength Electromagnetics: Theory and Applications." The course is designed to appeal to students with diverse academic backgrounds and broad scientific interests. Typically the class has included students from electrical, mechanical, and nuclear engineering, material science, chemistry, physics, and biophysics. In order to effectively reach this broad a class, course requirements are minimal: an introductory knowledge of Maxwell's equations, an undergraduate course in modern physics, and a mathematics background that permits integration in the complex plane. With this background the course attempts to explain advances in x-ray sources, brightness and coherence, scattering theory and refractive index, optics and instrumentation, and applications to the physical and life sciences that benefit from short wavelengths or high photon energies. These applications include x-ray microscopy and holography of sub-cellular biological material, printing of nanostructure patterns for future nanoelectronic devices, material studies of surfaces and thin films, the physics of hot dense plasmas, x-ray lasers and synchrotron radiation, and applications in physical chemistry.

Finally, we note that these class notes are partial in that several chapters did not make it at press time, including those on "X-Rays and Early Atomic Physics," and several chapters on aspects of scattering theory and refractive index at short wavelengths. Inclusion of additional material on applications and experimental technique are left for future versions.

In addition to the students who specifically contributed to this version of the class notes, and whose names appear with appropriate chapters, many other students contributed over the years through their enthusiasm for the material, their probing questions and pursuit of the subject through various class projects, homework assignments, field trips, and research activities on which they subsequently embarked.

Dr. Kwang-Je Kim is gratefully acknowledged for his patient tutoring on many aspects of synchrotron radiation. Professor Nathan Marcuvitz is remembered for stimulating lectures on the subjects of plasma dynamics and electromagnetic theory, material that we follow closely in several places. Dr. James Underwood and other colleagues at the Center for X-Ray Optics are warmly acknowledged for the advice and guidance they have freely and expertly given both to me and to students over the years as they pursued class projects and oral presentations on special topics. Finally, Dr. Howard Schlossberg and the Air Force Office of Scientific Research are acknowledged for their continuing encouragement and financial support of this student training project.

David T. Attwood
Berkeley, California

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